Laptop Adaptor Using a Piezoelectric Transformer
-Drive Circuit Development-

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Abtract

This paper describes incorporation of a piezoelectric transformer into a laptop computer adaptor in order to miniaturize the size and improve the energy utilization. Conventionally, electromagnetic transformer is used in the adaptor for generating the 45W output power. In this study, we show that a multilayer piezoelectric transformer rated 30W output power can satisfy the laptop specifications. The multilayer piezoelectric transformer prototype 27 mm in diameter and 4.7 mm in thickness, operated at 83 kHz under radial mode excitation was fabricated. The drive circuit was operated under near zero voltage switching condition for lowering switching loss. Consequently, the laptop adaptor was made with less than a half of its electromagnetic in volume.

Introduction

Laptop computers have been extremely powerful and compact. In contrast, the adaptor is still too bulky due to electromagnetic transformer size. To cut down the adaptor size, the transformer is necessary to be smaller. One suited option is a piezoelectric transformer.

Piezoelectric transformers (PT), using converse and direct piezoelectric properties of ceramic materials, were first introduced by Rosen in 1956 [1-2]. These invented transformers had a major reliability problem due to breakdown at the center position. Many researchers have attempted to improve reliability by redesigning the electrode configuration. Kawashima et al. used the third order longitudinal mode of the Rosen-type to power backlight inverter [3]. Koc et al. introduced a circular piezoelectric transformer with crescent shape input using a shear mode (k_{15}) electromechanical coupling constant which is normally twice as large as the transverse mode coupling (k_{31}) for voltage step up application [4]. However, maximum power transfer of the single layer transformer is not sufficient for high power application, such as laptop computer adaptors (~30W). The multilayer transformers were the break through option for power barrier.

In this paper, we implemented a multilayer circular piezoelectric transformer with crescent shape output electrode for voltage step down type. The key is the driving either input electrodes or the output electrodes the same radial mode of the whole disk is excited at a very close frequency range. This is a key point that makes the transformer preferable over other PTs. By making multilayer with co-firing technology, the power handling was increased. Furthermore, we developed a small (less than half of its electromagnetic adaptor) and simple drive circuit, which employs Zero Voltage Switching (ZVS) techniques by adding the dead time for a half bridge inverter. These techniques have been recognized as switching loss and voltage stress suppression to switching elements [5]. In other words, the ZVS significantly reduces the capacitive turn-on loss due to input capacitance of PT [6].

Multilayer Circular Piezoelectric Transformer Design for Step Down Laptop Adaptor

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The transformer was designed as a step down type. The transfer function of the piezoelectric transformer operating at the resonance frequency can be approximated as [7]

$$\left|\frac{V_{out}}{V_{in}}\right| = \left|\sqrt{2}\,\frac{m_i A_i}{m_o S_o}\right| \quad (1)$$

where m_i is the number of the input layers, m_o is the number of the output layers, A_i is the effective area of the input, and S_o is the effective area of the output.

With this relationship, we can determine the areas and the number of the input and output layers to meet the power requirements for start up condition. We would demonstrate the adaptor function for Toshiba Dynabook SS laptop. This computer required $15V_{dc}$ and 1.3A for the startup requirement and $15V_{dc}$ and 0.8A for steady state condition. The ratio $\frac{m_i}{m_o}$ was taken to be 0.5 and the ratio $\frac{A_i}{S_o}$ was then determined to satisfy the startup requirement, and some safety factor for compensating high power voltage regulator efficiency. In our case, we arbitrarily pick 10%.

Figure 1 shows the structure [8] of input and output of the piezoelectric transformer. Note that the thickness is also determined to match loading impedance using Eqs (2) and (3).

$$C_o = \frac{e\, m_o S_o}{t} \quad (2)$$

$$\left|Z_L\right| = \frac{1}{w_i C_s} \quad (3)$$

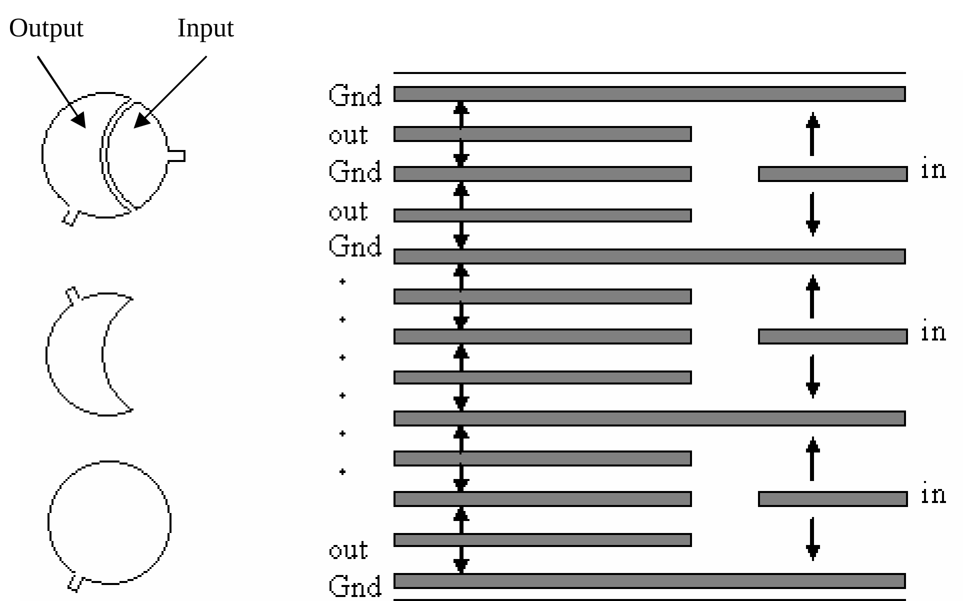


Figure 1 Structure of the Piezoelectric Transformer.

where C_o is the output capacitance, e is permittivity, t is output thickness, Z_L is loading impedance, and w_i is the resonance frequency when output is short-circuited.

AC-DC Drive Circuit Principles

The drive circuit can power up the laptop to 30W without a feedback signal. As a result, the circuit is very compact and simple. The circuit contains 5 portions; Off line Voltage Regulator, Pre-Rectifier, Inverter with ZVS, Rectifier, and High Power Voltage Regulators.

The Off line Voltage Regulator is composed of two capacitors, one MOSFET, and the other IC SR036 made by Supertek. The regulator acts as the 15V DC power supply out of the 120V household outlets. The operating principle can be found in [9]. The Pre-Rectifier comprises four diodes and one filter capacitor which forms full bridge rectifier. The off line voltage Regulator and Pre-Rectifier are shown in Figure 2. The filter capacitor was chosen to be so large that the ripple voltage is negligible. However, picking a too big capacitor is not the answer for the miniaturization. We picked 33 mF at 250V.

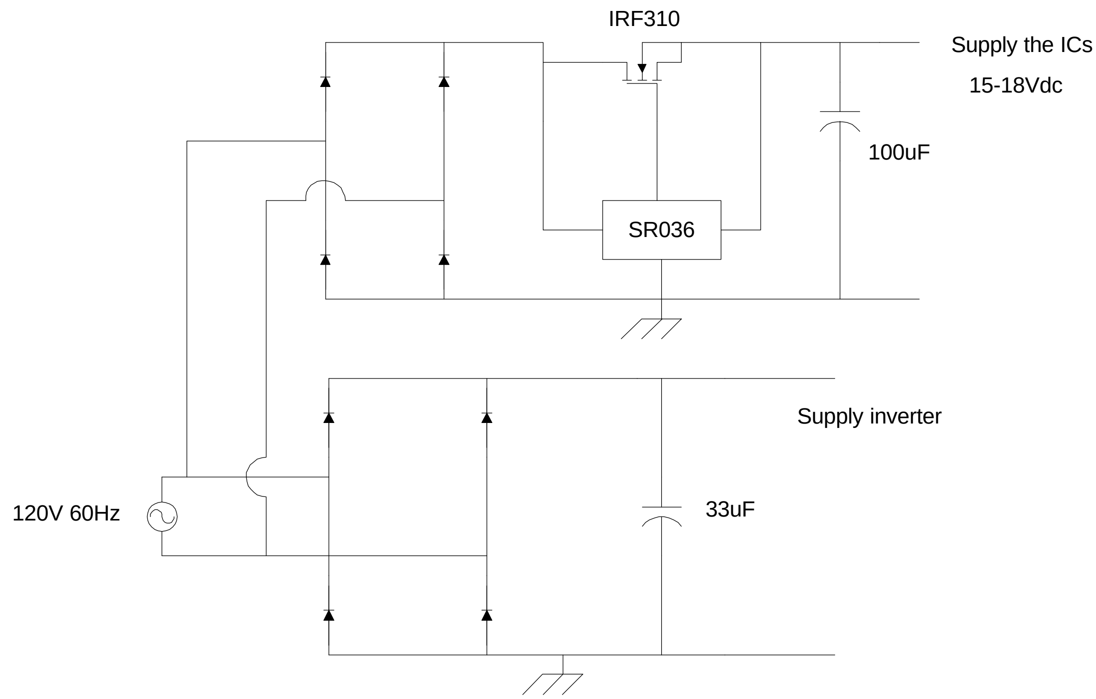
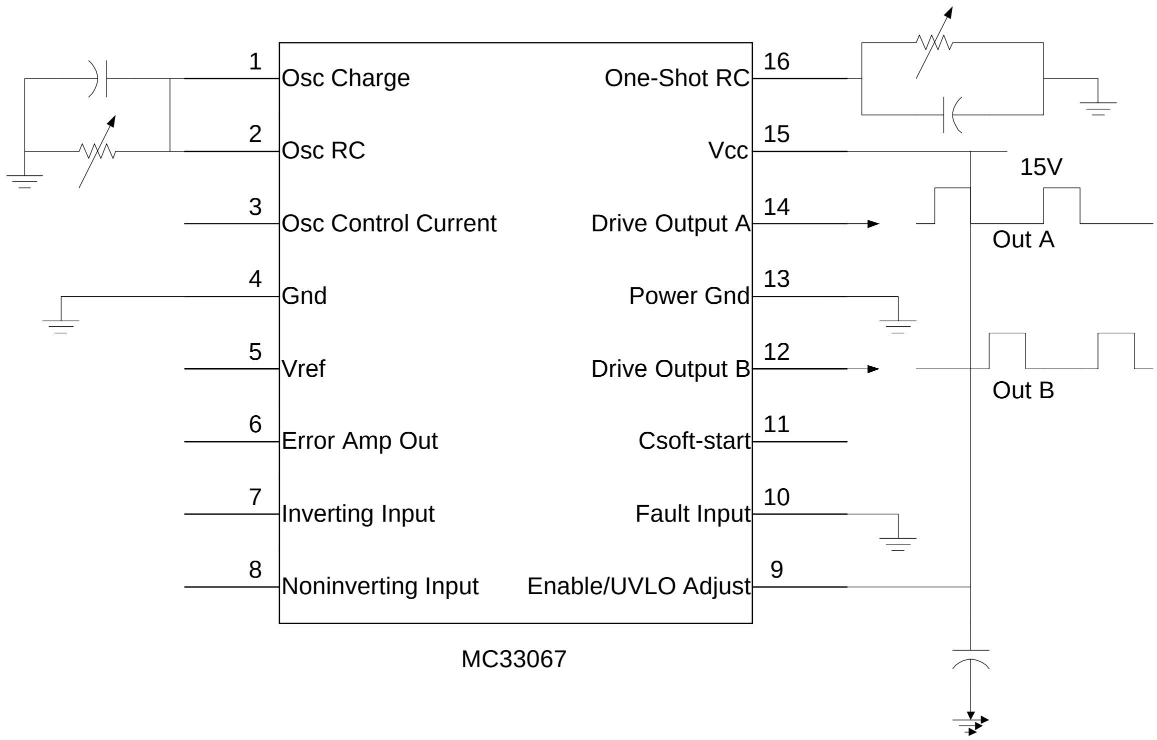


Figure 2 Off line Voltage Regulator and Pre-rectifier with Full bridge rectifier.

The inverter is made of MC33067 (2 synchronous clocks with a certain dead time), IR2112 (Hi-Low Side Driver), two MOSFETS (IRF740), one matching inductance, and the piezoelectric transformer as shown in Figure 3. The MC33067 generates two clocks signal fed to the IR2112. The duty cycle is picked such that the ZVS condition [10] is achieved and the circuit is delivered enough power. In other words, too small duty cycle does not provide power transfer and 50% duty cycle leads to too much loss in MOSFETS (heat generated in transistors). The two MOSFETS forms half bridge inverter which is driven by the IR2112. Then the matching inductance is express as

$$L_{matching} = \frac{1}{w_i^2 C_i} \tag{4}$$

where w_i is resonant frequency and C_i is an input clamped capacitor.



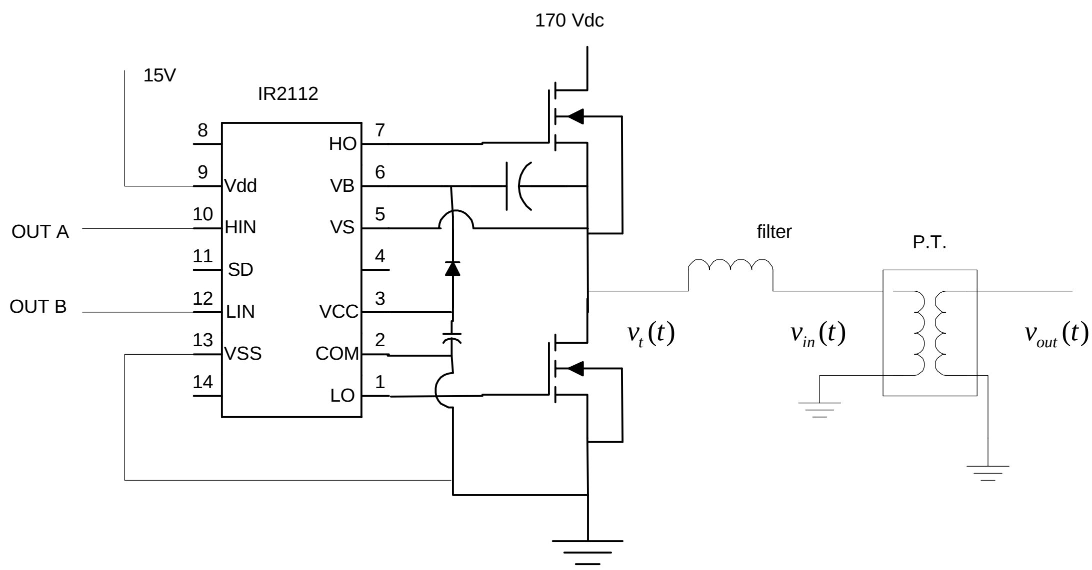


Figure 3 Half-bridge Inverter with matching inductor and Piezoelectric Transformer.

The added inductor filters the high frequency out but lets the resonance and lower frequencies (w_i , and DC value) pass. The resonance frequency excites the piezoelectric transformer but DC value gets charged into a clamped capacitor C_i of the transformer.

Next, the full bridge rectifier is connected to the piezoelectric transformer. At the output of the rectifier,$15V_{dc}$ or higher is expected at all time of operation. Finally, two high power voltage regulators were installed in parallel to create constant 15Vdc because one voltage regulator can provide three amp and 15V. Figure 4 shows the full bridge rectifier connected to one high power voltage regulator.

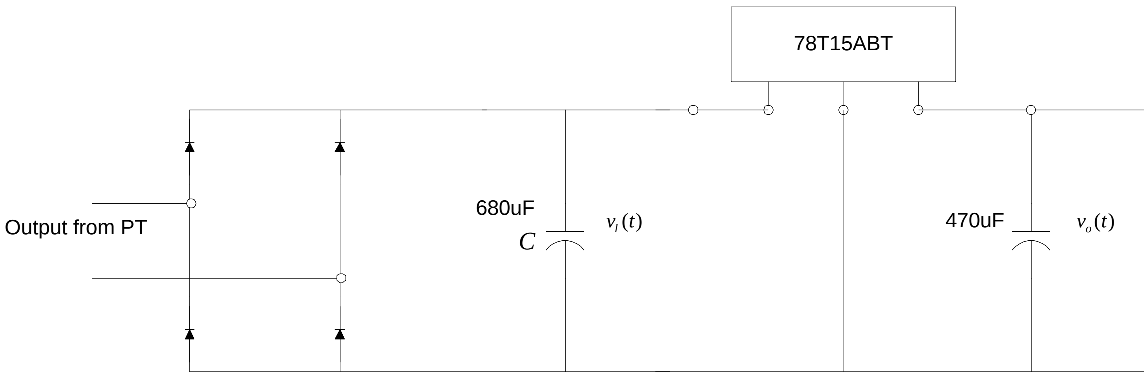
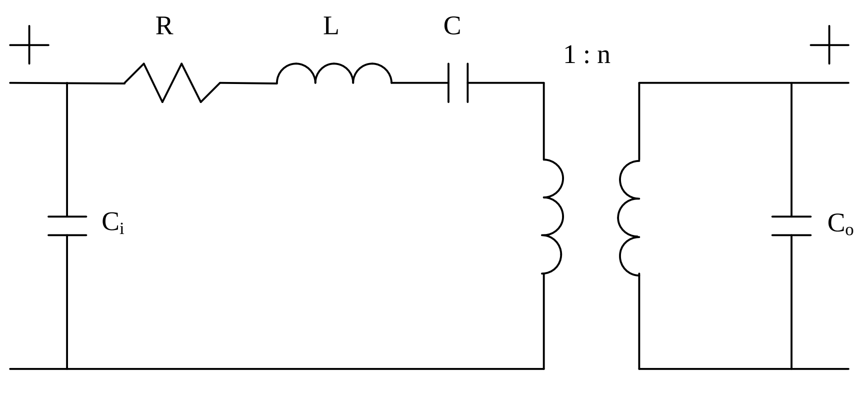


Figure 4 Full-Bridge Rectifier Connected to Voltage Regulator.

Experimental Set Up and Results

The piezoelectric transformer in this application was fabricated using NA type material developed by Taiheiyo Cement Co, Japan with co firing technology. The optimal number of the input and output layers were 6 and 12 respectively using Eqs. (1)-(3). Each input and output layer had 0.78 mm and 0.39 mm. The transformer disk of 4.7 mm. in thickness and 27 mm in diameter was sputtered with platinum electrode according to the proposed configuration.

In order to identify the operating frequency of the transformer, the input and output terminals were measured by the HP4194A impedance/gain-phase analyzer under short circuit test and fitted curve using a C-RLC equivalent circuit as shown in Figure (5). The matching impedance was estimated to be 18.5 ohm ($=\frac{1}{wC_o}$), at 0.3 step-up ratio. Since most of the time the laptop operated in steady state mode, it was best to match the load at steady state condition as well as sufficient output voltage at start up condition.



$$C_a = 20.6\text{nF},\ R = 1.79\ \Omega,\ L = 1.72\text{mH},$$
$$C = 2429\text{nF},\ C_s = 113.1\text{nF},\ n = 0.3$$

Figure 5 Equivalent Circuit of the PT and its parameters.

The transformer voltage step-up ratio and efficiency were tested under various impedances including matching impedance with constant output power, see Figure (7). From these curves, the operating frequency was picked at 83 kHz instead of 85 kHz (highest efficiency) to have sufficient voltage gain.

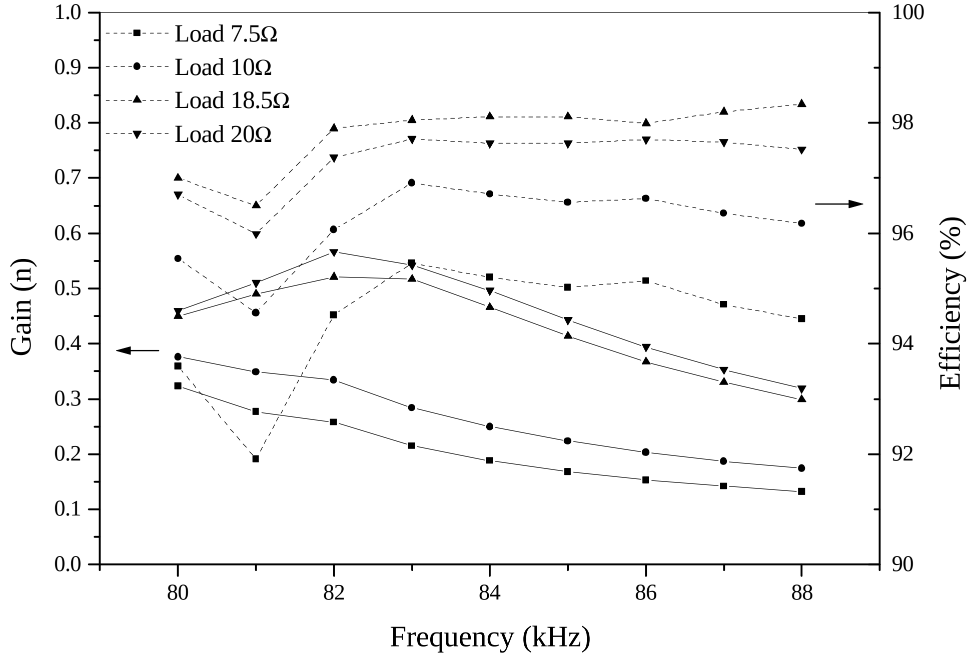


Figure 6 The PT Voltage Gain and efficiency vs frequency at various loads.

Figure 8 shows the relation between output power and ceramic temperature rise tested on 18.5 ohm load. It is evident that the PT can supply more than 26W under 25C^{o} temperature rise which is sufficient for the laptop adaptor. However, under transient condition PT can supply over 30W.

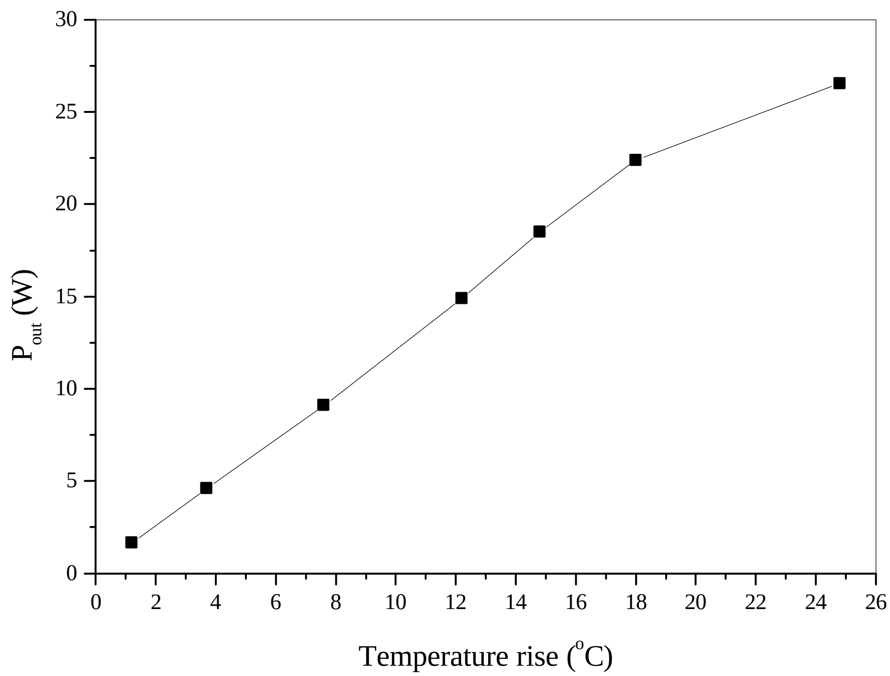


Figure 7 The temperature rise as a function of output power.

The transformer and circuit were connected as shown in Fig (2), (3), and (4) and tested with the laptop. From Figure 8(a), the operating frequency, duty cycle and matching inductance were tuned to 83 kHz, 42%, and 180 mH , respectively. Figure 8(b) shows all voltage waveforms. The voltage V_{in} represents voltage applied to the transformer. The voltage V_{out} denotes the voltage at the output of the transformer. And the voltages V_l and V_o are the voltages applied to the regulator and out of the regulator.

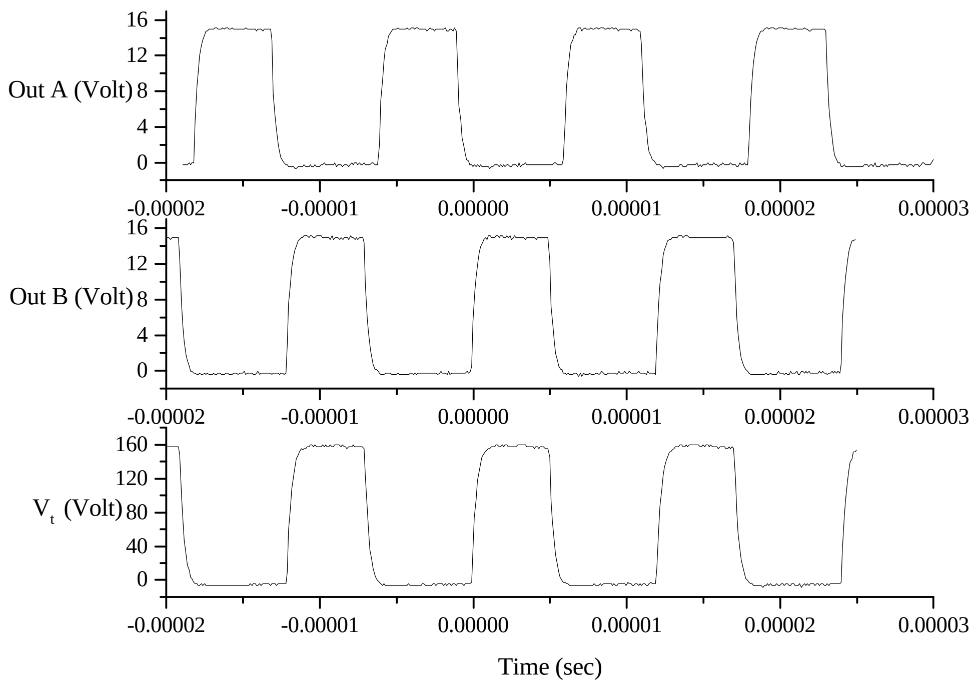


Figure 8(a) Voltage waveforms of the outputs A and B and applied voltage between inductor and inverter.

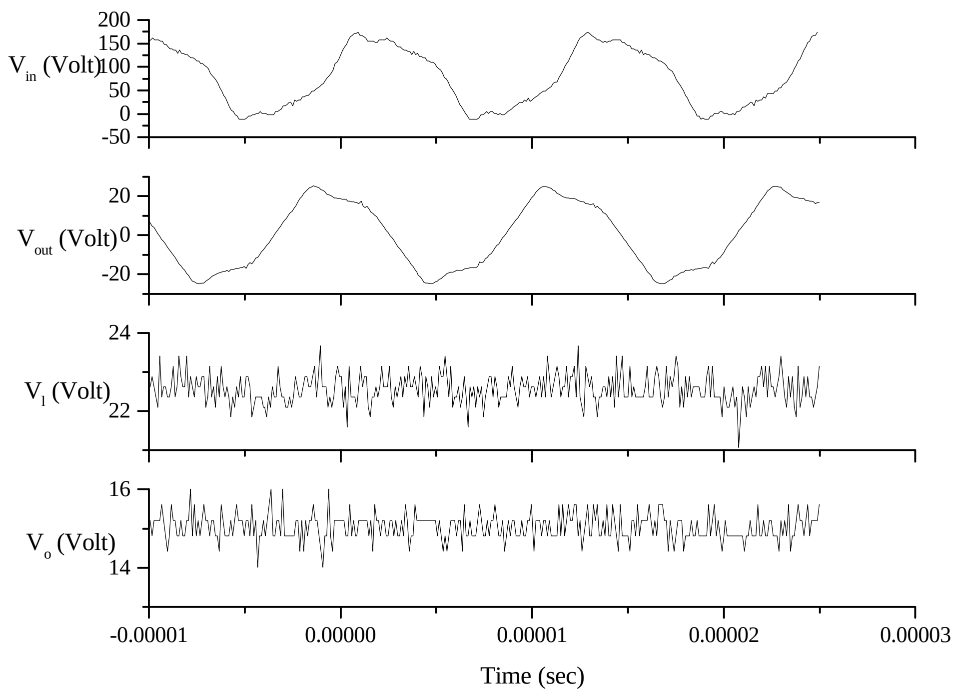
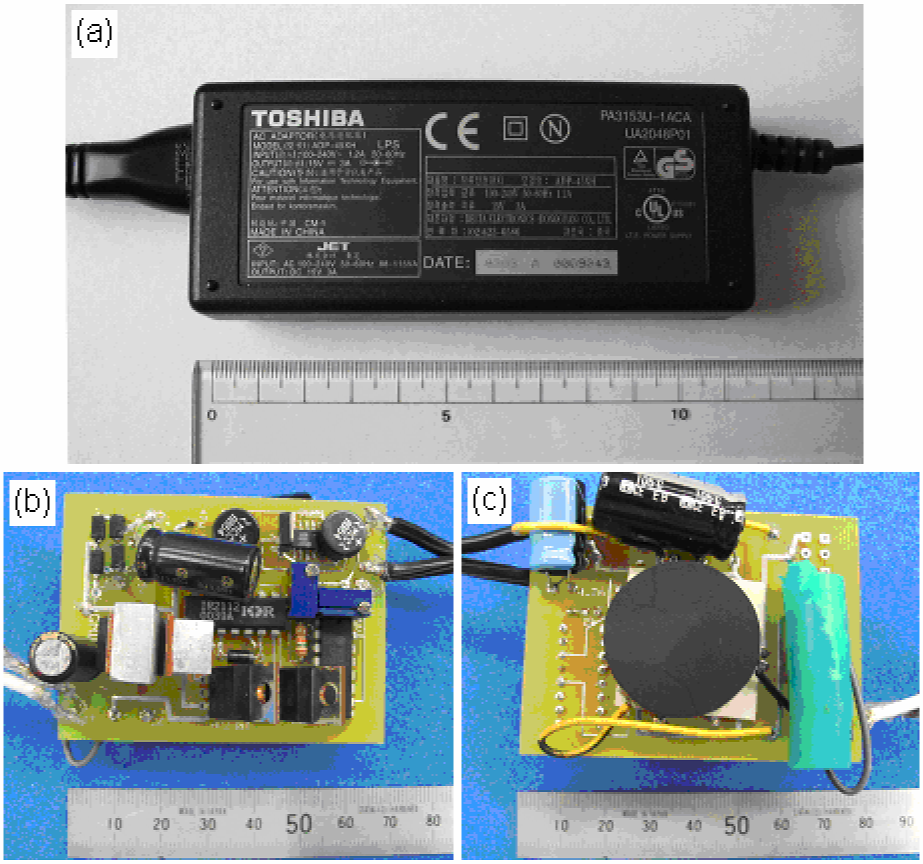


Figure 8(b) Voltage waveforms at various points.

Figure (9) shows the comparison between piezoelectric transformer adaptor and its original adaptor. Obviously, the new piezoelectric transformer adaptor was less than half of its electromagnetic adaptor in volume. The dimension of electromagnetic adaptor was 105mm in length, 54mm in width, and 28mm in thickness resulting in 130,000 mm^3. Meanwhile the dimension of our piezoelectric adaptor was 64mm in length, 49mm in length, and 15mm in thickness resulting in 47,000 mm^3.



(Fig. 9) Figure 9 Comparison of the Toshiba Laptop Adaptor and the PT designed laptop adaptor; (a) original Toshiba laptop adaptor, (b) front image of the PT designed laptop adaptor, (c) back image of the PT designed laptop adaptor.

Conclusions

The high power step down type piezoelectric transformer was used in the AC-DC laptop adaptor. The piezoelectric transformer with matched drive circuit successfully replaced the 30W laptop adaptor. The drive circuit was simple, compact, and required no feedback signal. As a result, the adaptor volume was significantly reduced more than half, compared to the manufacturer's electromagnetic adaptor.

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